

The Jura fold-and-thrust belt: a kinematic model based on map-balancing

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ABSTRACT

The Neogene thin-skinned Jura fold-and-thrust belt is a crescent shaped feature which branches off from the Western Alps and almost subparallels the deformation front of the Central Alps over a distance of 300 km. Its geometry is largely preconditioned by the distribution of Triassic salts which act as a basal detachment horizon. Regional balanced cross-sections indicate that bulk shortening in the Jura orocline increases from zero at its northeastern termination to about 30-32 km at the southern termination of the Central High Jura. During the deformation of the Jura fold-and-thrust belt, the Molasse Basin, located between it and the Alps, was stably displaced northwestwards by a similar amount above a basal Triassic detachment layer.

Development of the Jura fold-and-thrust belt is probably kinematically related to the uplift of the basement involving external massifs of the Alps which acted as crustal-scale back-stops. Theoretical considerations and analogue models indicate that the initial taper of the undeformed Molasse wedge was equal to the critical taper; in contrast the initial taper of the internal parts of Jura was

below the critical taper and thus became the locus of strain concentration. Availability of an effective viscous basal layer allowed for in- and out-of-sequence thrust propagation during the Jura deformation.

Northwestwards displacement of the Jura-Molasse nappe involved radial outward directed mass transport, facilitated by wrench faulting. Southwestwards increasing bulk shortening, accompanied by an apparently 10° clockwise rotation of the detached Molasse Basin, is related to Neogene differential westwards displacement of the Mont Blanc-Aiguilles Rouges Massif relative to the Aar Massif.

INTRODUCTION

The northwest verging, arcuate Jura fold-and-thrust belt is a typical arcuate mountain range which branches off from the Western Alps near Chambéry and extends over a distance of some 300 km to the North of Zürich where it dies out

PHILIPPE, Y., COLLETTA, B., DEVILLE, E. & MASCLE, A., 1996. — The Jura fold-and-thrust belt: a kinematic model based on map-balancing. In: ZIEGLER, P. A. & HORVÁTH, F. (eds), *Peri-Tethys Memoir 2: Structure and Prospects of Alpine Basins and Forelands*. *Mém. Mus. natn. Hist. nat.*, 170: 235-261 + Enclosures 1-2. Paris ISBN: 2-85653-507-0.
This article includes 2 enclosures on a folded sheet.

near the eastern termination of the Lägern anticline. The Jura Mountains, which form the most external part of the West-Central Alpine orogen, have a maximum width of 70 km. They are separated from the Central Alps by the Molasse Basin which corresponds to a typical flexural foreland basin developed during Oligocene and Miocene times. In the western and northern parts of the foreland of the Jura the Bresse and Rhine grabens subsided from Late Eocene to Miocene (Aquitainian). These troughs are linked by the sinistral Rhine-Saône transform zone (Fig. 1a).

The Jura Mountains are upheld by folded and thrust Late Triassic to Middle Cretaceous carbonates and shales. In synclinal areas, Oligo-Miocene clastics are preserved which were deposited in the distal parts of the Molasse Basin and a depression which linked the latter with the Rhine Graben. During the compressional deformation of the Jura and Molasse Basin, spanning Middle Miocene to recent times (the "Jura phase" proper within the Jura fold-belt was active between about 10-6 Ma, according to Laubscher, 1987; 1993; Burkhard, 1990), Middle and Late Triassic evaporites played a major role as detachment horizons between the allochthonous cover and its apparently non-involved substratum, including the Hercynian basement, Permo-Carboniferous clastics contained in troughs the evolution of which is very complex kinematically, and Early Triassic clastics (Fig. 1b).

This paper aims at developing new (in addition to some old) geometric, kinematic and dynamic arguments on Jura development, on the basis of several sets of data:

- (1) field observations,
- (2) subsurface data (seismic and drillholes),
- (3) conventionally accepted mechanical models on fold-and-thrust belts and
- (4) analog viscous-brittle models.

Moreover, we attempt to propose a kinematic analysis of the deformation of the Jura thrust belt, based on a balanced palinspastic map constructed from a series of restored regional cross-sections.

Structural Zonation of the Jura Thrust Belt

On the basis of contrasting structural styles, the Jura thrust belt can be subdivided into an internal and an external zone (Chauve et al., 1980):

The Internal or High Jura is characterized by large overthrusts, at least in the southern and central parts of the belt, such as the Mont Tendre thrust and the Risoux nappe (see Encl. 1, section n°4; Winnock, 1961; Bitterli, 1972), whereas box-folds, in which post-Triassic series are detached from the basement, locally affected by reverse faults and/or back-thrusts (Laubscher, 1965, 1977), predominates in the eastern Jura. The transition to the Molasse Basin is generally sharp where Mesozoic series appear to be little affected by compressional deformations. An exception is the southwestern most part of the Molasse Basin where Mesozoic strata crop out in ramp anticlines, such as the Mont Salève (Guellec et al., 1989, 1990a and 1990b; Wildi and Huggenberger, 1993; Deville et al., 1994).

The **External Jura** comprises four tabular plateaux which are devoid of major compressional structures. These are delimited by an array of narrow, strongly tectonized zones, corresponding to Late Eocene to Oligocene extensional structures which were reactivated during the folding of the Jura by convergent wrench and compressional movements (the so-called "pinçées" in the sense of Glangeaud, 1949; Chauve and Perriaux, 1974). The external deformation front of the Jura is characterized by relatively narrow zones of imbricate thrust sheets. Such thrust sheets override the margin of the Bresse Graben (Lienhardt, 1962; Enay, 1982; Chauve et al., 1988; Philippe, 1991) whereas upright box-folds encroach on the southern margin of the Rhine Graben.

Evolution and Tectonic History

The stratigraphic column given in Fig. 3 outlines the lithostratigraphy of the Jura Mountains and highlights regional and local detachment horizons. Tectonic stress conditions dominating the

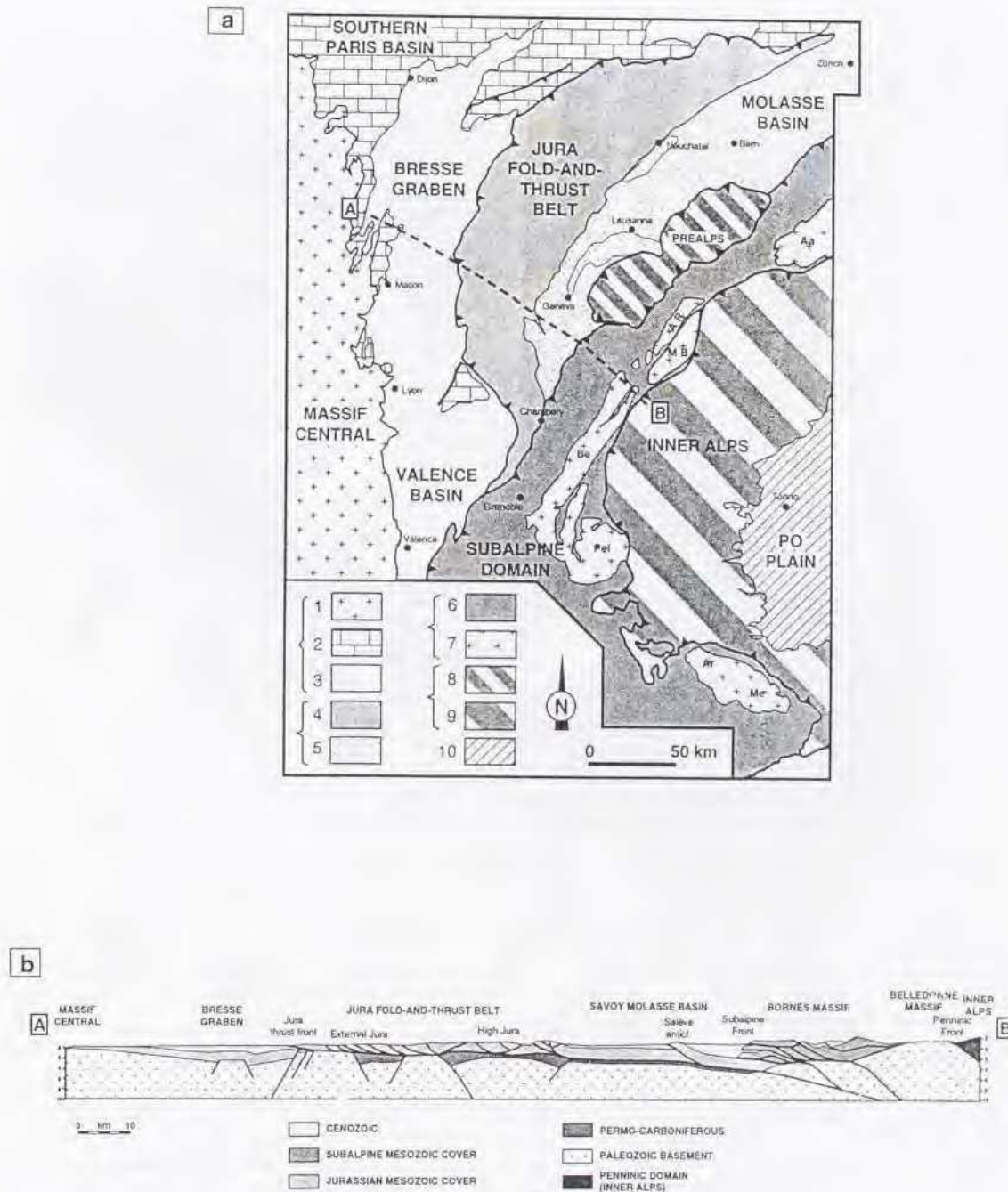


FIG. 1a. Schematic structural map of western Alps and foreland.

1-3: Stable Western European craton (1: basement, 2: Autochthonous Mesozoic sediments, 3: Tertiary sediments); 4-5: Alpine foreland (4: Mesozoic sediments of Jura thrust belt, 5: Neogene molasse); 6-7: Subalpine domain (6: Mesozoic sediments, 7: basement); 8: Internal Alps and Swiss Prealps; 9: Southern Alps.

External Crystalline massifs: Aa: Aar; AR: Aiguilles-Rouges; Be: Belledonne; MB: Mont Blanc.

FIG. 1b. Schematic cross-section through western Alps and their foreland, along the ECORS deep seismic profile (Bergerat et al., 1990; Guelléc et al., 1990a; modified).

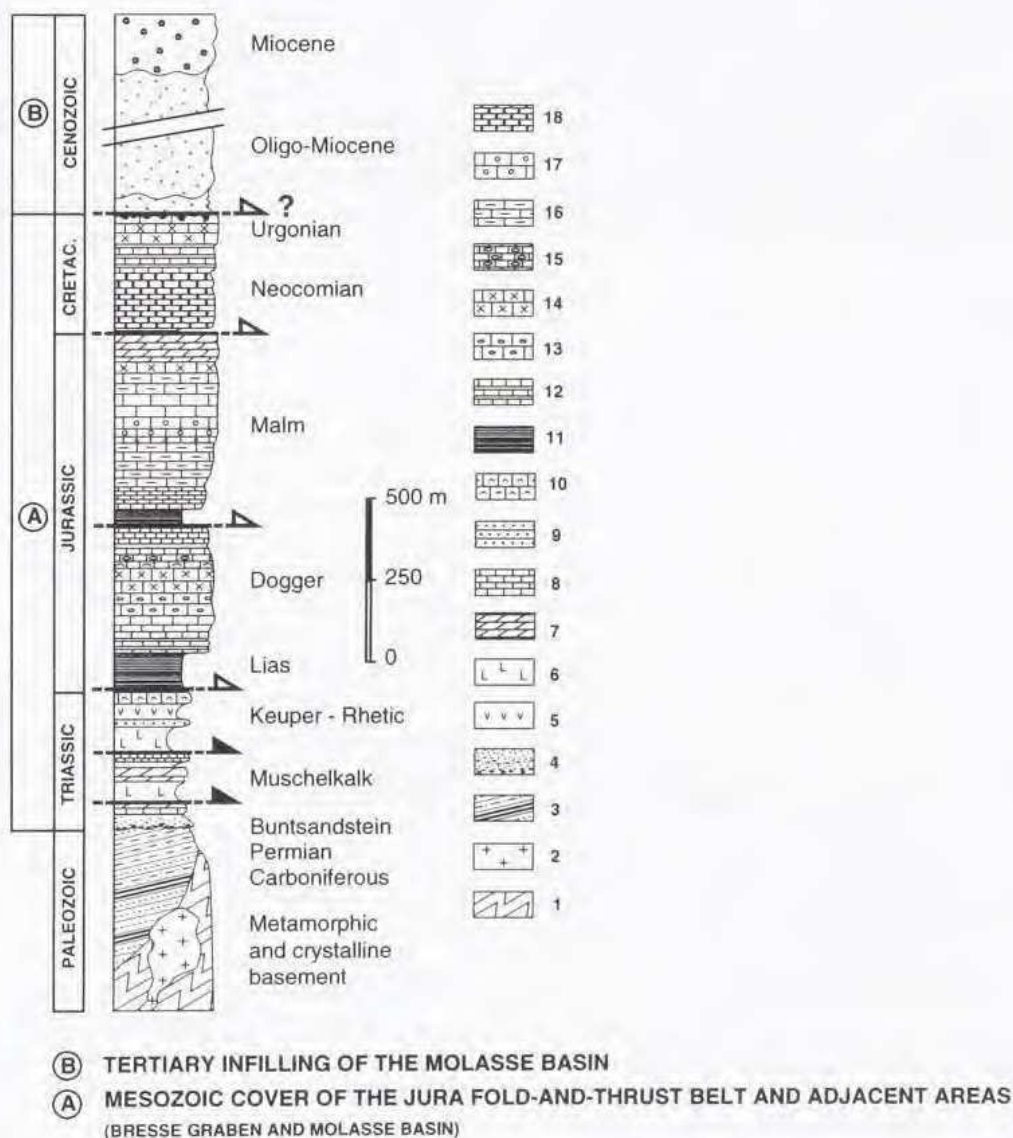


FIG. 3. Summary lithostratigraphic column of Mesozoic and Tertiary series of the Jura and the Molasse basin.

Arrows indicate potential décollement levels (black arrows show the location of the two regional sole thrusts, Eastern Jura: Middle Muschelkalk salt; Central and Southern Jura: Early Keuper salt).

1: Metamorphic basement; 2: Granites; 3: Coal-measures and black shales; 4: Conglomerates, pebbles and sandstones; 5: Evaporites; 6: Massive salt layers; 7: Dolomites; 8: Limestones; 9: Sandstones; 10: Shelly limestones; 11: Marls; 12: Alternating marls and limestones; 13: Oncolitic limestones; 14: Reef limestones; 15: Cherty limestones; 16: Argillaceous limestones; 17: Nodular limestones; 18: Bioclastic limestones.

area of the Jura Mountains during Late Palaeozoic to Cenozoic times are summarized in Fig. 4.

The Jura Mountains and adjacent areas are underlain by a basement complex, consisting of metamorphic and intrusive rocks, which was consolidated during Carboniferous phases of the Variscan orogeny. This basement mainly crops out in the Massif Central, the Vosges and Black Forest, and in the external massifs of the Alps. In addition, it was reached by numerous boreholes drilled in the Bresse Graben, the external Jura and the Molasse Basin.

During Stephanian-Autunian times, a system of mainly transtensional, narrow and deep, fault-bounded basins subsided in which partly coal-bearing and lacustrine bituminous shales accumulated. Detailed structural analyses of Permo-Carboniferous basins of the Massif Central indicates, that they evolved under changing stress conditions, causing their partial inversion at the transition to the Late Permian (Blès et al., 1989; Ziegler, 1990).

Borehole and reflection seismic lines indicate that such basins underlay also parts of the Jura thrust belt as well as parts of the adjacent Molasse Basin (Fig. 5; Arthaud and Matte, 1977; Laubscher, 1986, 1987; Ziegler, 1990). In northern Switzerland, the main Late Paleozoic trough ("Constance-Frick basin") subparallels the eastern part of the belt. Its southern margin has been reactivated in the Early Tertiary and afterwards acted as loci for the development of thrusts during the Jura phase (Laubscher, 1986; see Encl. 1, sections n°7 and n°8), thus controlling structural trends and the deformation style of the eastern Jura.

During the Late Permian, the area of the Jura formed part of a northeasterly trending broad depression in which essentially continental series were deposited. These conditions of continental sedimentation prevailed during the Early Triassic, but as evinced in the Swiss Jura and Central High Jura, the Buntsandstein overlies discordantly the Permo-Carboniferous troughs (see Encl. 1, section n°4).

During the Middle Triassic, marine transgressions entered this basin from the northeast as well as from the southwest, giving rise to the accumulation of the Muschelkalk carbonates and evaporites. Late Triassic regressive conditions are indicated by the deposition of the Keuper red beds and salts. During Triassic times the area of sedimentation

expanded progressively into the domain of the Paris Basin and links were established with the basin of southeastern France (Debrand-Passard et al., 1984) from which marine transgressions entered the area of the Jura at the onset of the Jurassic. During Early Jurassic times, a broad, shallow marine shelf was established which extended northwards into the Paris Basin and the Northwest European Basin. To the south, this shelf was limited by the so-called Alemannic high, running obliquely across the Aar Massif, which partly separated it from the Tethys shelves. Regional isopach maps and the distribution of Middle and Late Triassic salts (Fig. 6) indicate that the area of the Jura Mountains corresponded during Triassic and Early Jurassic times to a differentially subsiding basin, referred to as the Burgundy Trough. This trough formed part of the regional Triassic-Early Jurassic Arctic-North Atlantic and Tethys rift system. Upon achievement of crustal separation in the Tethys during early Middle Jurassic times, the Burgundy Trough ceased to subside differentially. Middle and Late Jurassic carbonates and shales were deposited on a broad shelf which reached from the Helvetic Tethys margin into the Paris Basin and southern Germany. These tectonically relatively stable shelf conditions apparently persisted throughout Cretaceous times (except probably in the eastern Jura; Laubscher, 1995, pers. comm.), with basin margins being controlled by major fluctuations in relative sea-level (Ziegler, 1990).

During the Early Paleocene, the Late Cretaceous carbonate shelf was destroyed in response to the build-up of tangential compressional stresses, reflecting increasing collisional coupling between the Alpine Orogen and its foreland. Resulting broad lithospheric deformations caused regional uplift of the western Alpine foreland (including the area now occupied by the Molasse Basin and the Jura Mountains) and deep truncation of the Cretaceous and Late Jurassic sedimentary cover. During Late Eocene times the Rhine and Bresse grabens, which form part of the Cenozoic rift system of Western and Central Europe, started to subside while thrust-loaded subsidence of the Helvetic Shelf commenced. From Oligocene to Early Miocene, the evolving flexural Alpine foreland basin expanded northwards. Continued crustal extension in the Rhine and Bresse grabens was

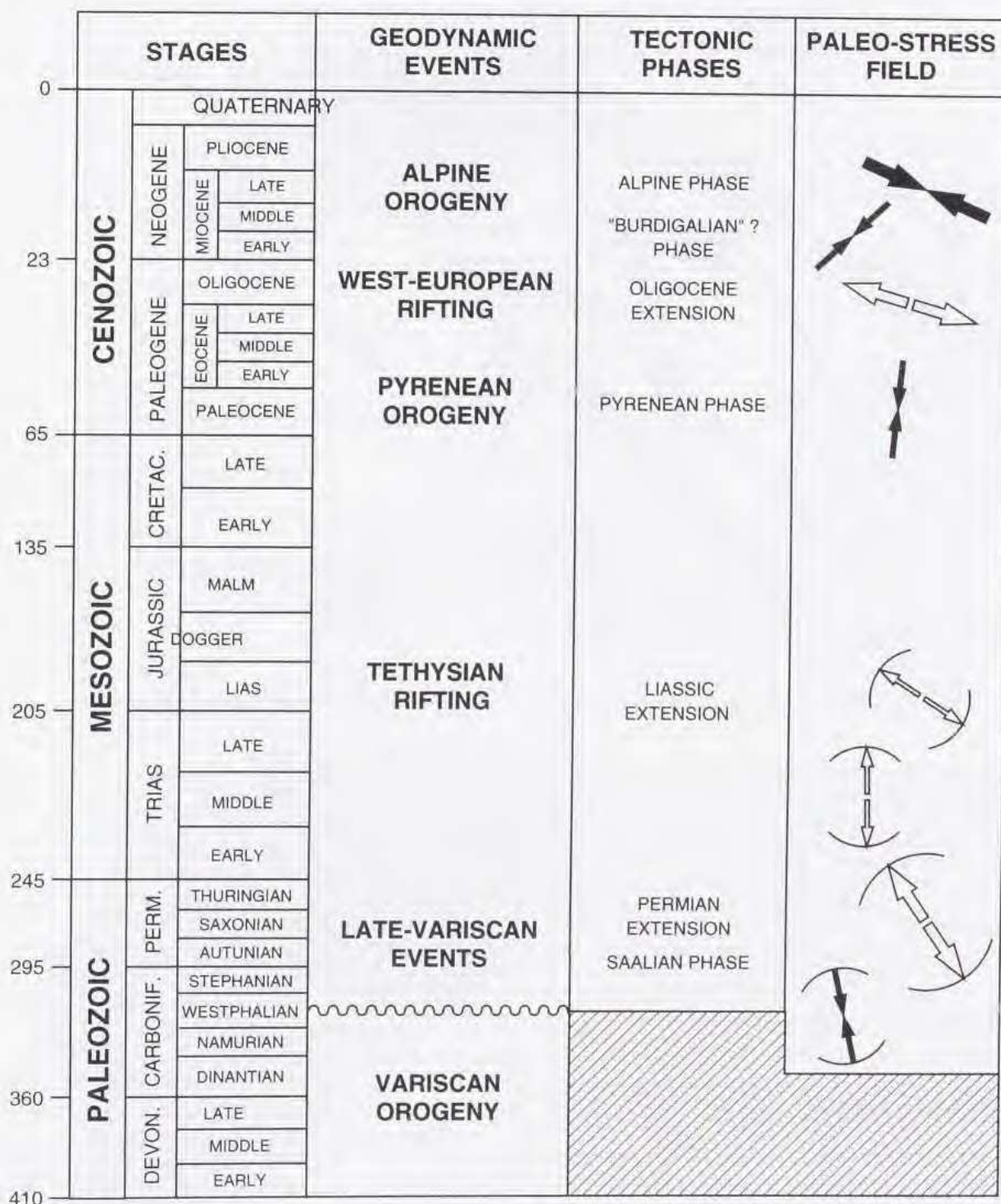


FIG. 4. Tectonic events recorded in the Jura domain.

Black arrows: maximum (s_1) principal stress axis; open arrows: minimum (s_3) principal stress axis.

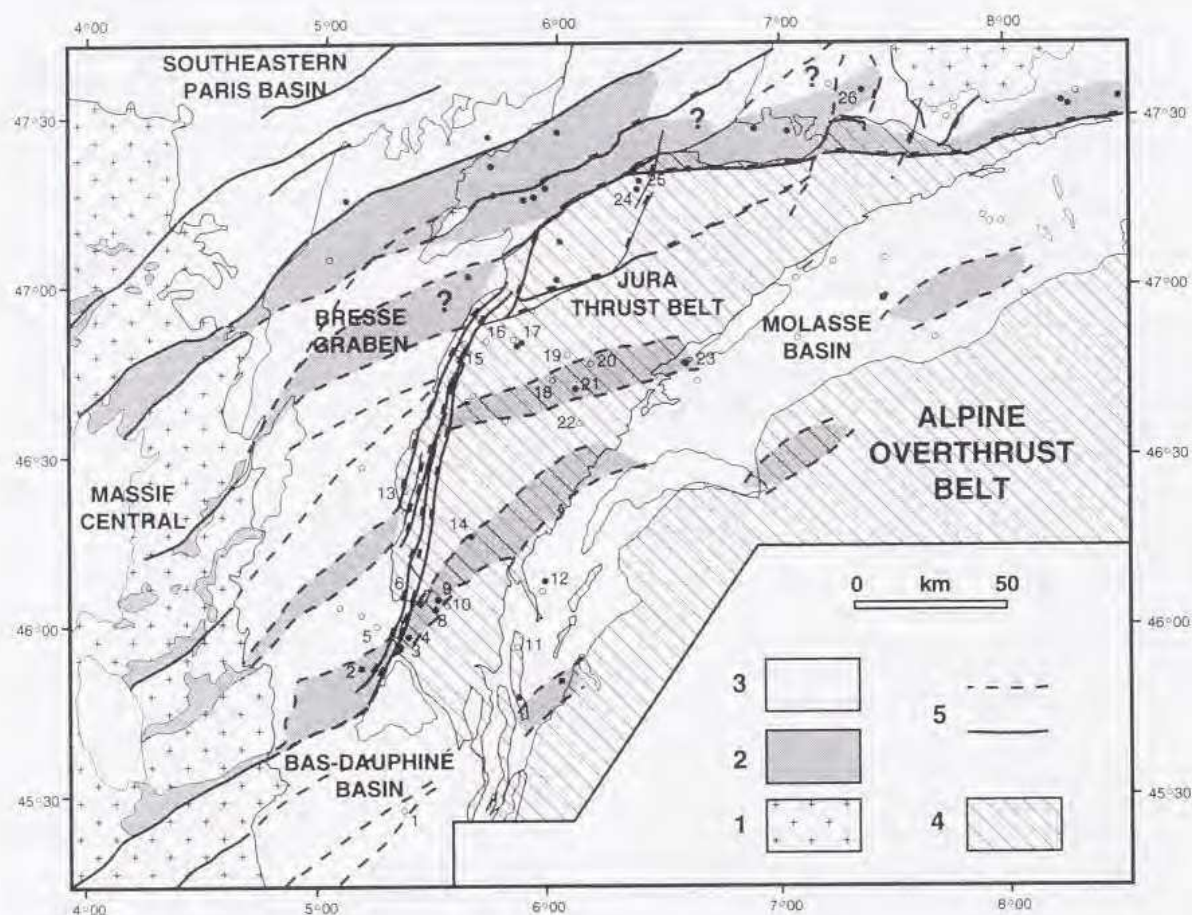


FIG. 5. Relationship between basement faults and the location of the Jura thrust front. The deep-seated basement faults in the Bresse graben are inferred from gravimetry data (BRGM, 1980; Truffert et al., 1990; modified).

1: Autochthonous Palaeozoic crystalline basement; 2 Late Variscan Permo-Carboniferous troughs (outcropping, drilled or imaged on seismic profiles); 3: Autochthonous Mesozoic cover and Tertiary sediments; 4: Jura fold-and-thrust belt and Western Alps; 5: Late Variscan deep-seated lineaments.

Boreholes: 1: Paladru; 2: Blyes; 3: Vaux-en-Bugey; 4: Torcieu; 5: Cormoz; 6: Bugey 101; 7: Bugey 102; 8: Chatillon; 9: Chaleyriat; 10: La Chandelière; 11: La Taillaz; 12: Humilly; 13: Poisoux; 14: Charmont; 15: Lons-le-Saunier; 16: Grozon; 17: Valemoulières; 18: Toillon; 19: Essavilly; 20: Laveron; 21: Chatelblanc; 22: Risoux; 23: Treyvagnies; 24: Orsans; 25: Buez; 26: Knoërringue.

accompanied by the development of the sinistral Rhine-Saône transform zone which linked them. During the Miocene, a tectonically controlled depression developed, crossing the area of the future Jura in the prolongation of the Rhine Graben, through which communications were established between the latter and the Molasse Basin (Ziegler, 1990, 1994).

Folding of the southern Jura Mountains initiated during the Burdigalian as evident by syn-tectonic Miocene strata located in front of the forelimb of the Gros Foug thrust-fold (Deville et al., 1994; see Encl. 1, section n°2). The main folding phase spanned Seravallian to Tortonian times (Laubscher, 1987). However, compressional deformation of this fold-and-thrust belt continued during Pliocene times and, based on geodetic data and morphologi-

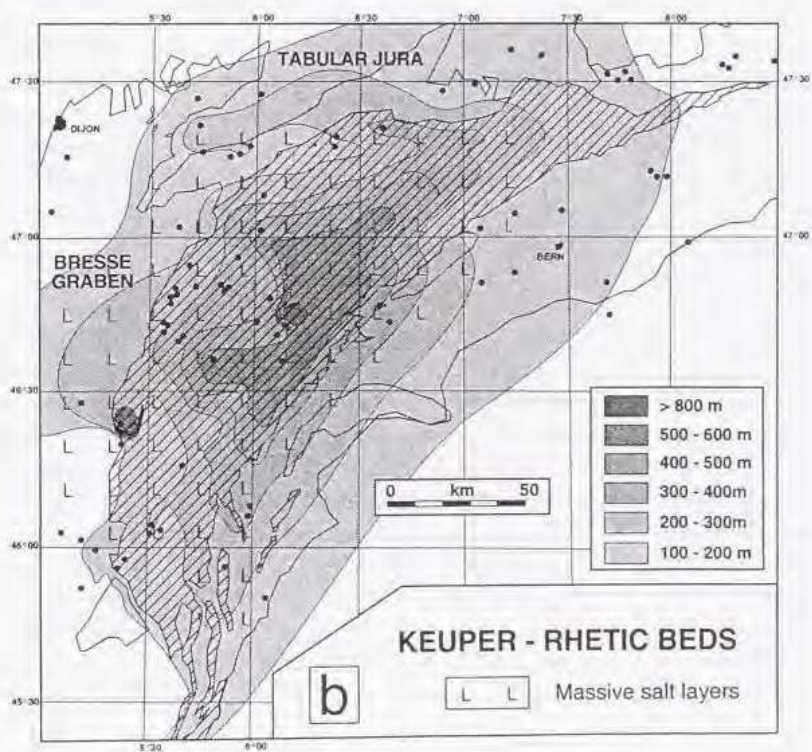
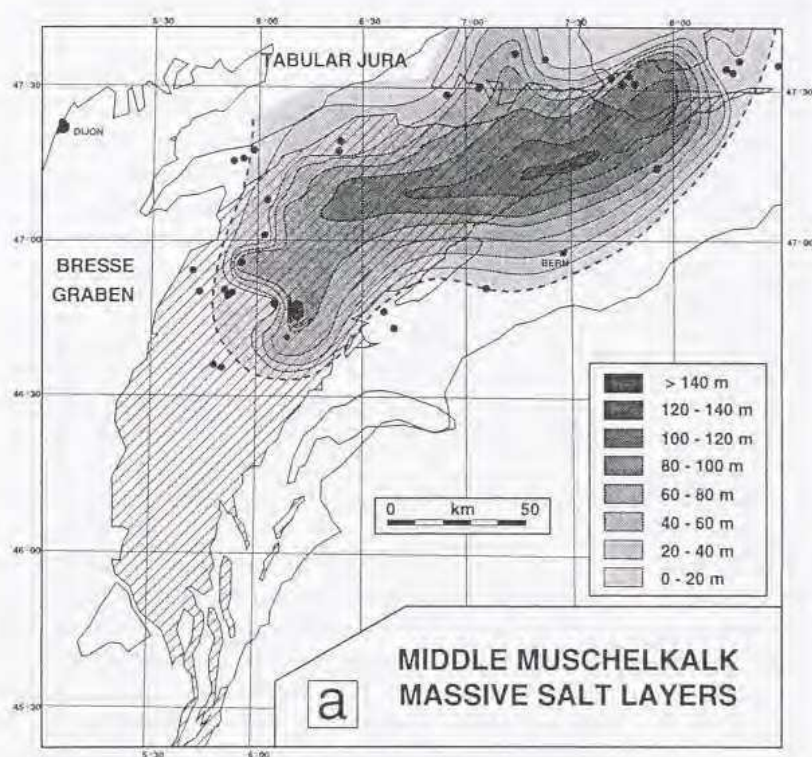


FIG. 6. Relationship between development of the Jura fold-and-thrust belt and the distribution of Triassic evaporites (thicknesses in meters).

a) Isopach map of the Muschelkalk massive salt layers.

b) Isopach map of the Upper Triassic (Keuper-Rhetic) layers (Lienhardt, 1984; modified).

Note that these maps are based only on well data, thus iso-values are tentative, especially in the eastern central part of the belt where no data are available.

cal criteria, persisted into the Recent (Fourniguet, 1978; Jouanne et al., 1995). During the development of the Jura fold-and-thrust belt, some Cenozoic extensional fault systems within the cover were compressionally reactivated, in particular the Rhinegraben faults and flexures (Laubscher, 1981), thus contributing to its present architecture. Moreover, its localization appears to have been preconditioned by the geometry of the Permo-Carboniferous half-grabens (see Encl. 1, sections n°7 and n°8; Laubscher, 1986) and the superimposed Early Mesozoic Burgundy trough in which the distribution of Triassic salts, acting as major detachment levels, played an eminent role (Fig. 6). In the latest stages of the Jura folding, post-dating thin-skin décollement, some of the Permo-Carboniferous crustal discontinuities were reactivated, causing local tectonic inversions of deep-seated Late Paleozoic troughs and related uplifts of both basement and the overlying deformed cover (see Encl. 1, section n°3; Philippe, 1994, 1995).

Geometry and Kinematics of the Jura Fold-and-Thrust Belt

As early as 1907, Buxtorf (1907, 1916) proposed a thin-skinned tectonic model for the Jura Mountains, involving detachment of the deformed Mesozoic and Cenozoic strata from the basement at the level of Triassic evaporites. Laubscher (1961, 1965) was the first to construct balanced cross-sections through this foldbelt and to quantify the bulk shortening achieved in it. Moreover, he developed the so-called "distant push" (Fernschub) hypothesis, according to which deformation of the Jura is mechanically coupled with the Alpine orogen by means of a regional sole thrust, located in Triassic evaporites. This thrust extends from the Alps through the Molasse Basin to the Jura Mountains where it splits and ramps up. As such, he considers the Molasse Basin as forming an integral part of the thin-skinned Jura allochthon. An alternate model was advanced by Ziegler (1982, 1990) who, based on reflection-seismic data from the Molasse Basin, proposed that an intra-crustal sole thrust, rooted along the northern margin of the Aar Massif extends through the Molasse Basin and

ramps up into sediments along the inner margin of the Jura Mountains.

In the following we discuss the set of regional balanced structural cross-sections and their palinspastic restoration, given in Encl. 1, and focus on the relationship between the Jura allochthon and the autochthonous basement. These cross-sections are based on surface geological data and, where available, integrate reflection-seismic and well data.

Section 1: Chartreuse Massif - Bas-Dauphiné Basin

This profile, which is partly constrained by reflection-seismic and borehole data, is located to the south of the area where the Jura orocline branches off from the Alps. The thickness and composition of the deformed sedimentary sequence is similar as in the Jura Mountains. The autochthonous basement dips gently eastwards under the allochthonous Chartreuse Massif. The sedimentary fill of the Bas Dauphiné Basin has been imbricated into a consistently west verging stack of narrow thrust sheets which are detached from the autochthon at a Late Triassic or more likely at an Early Jurassic (Aalenian?) level. Triassic series are extremely reduced and devoid of evaporites and rocksalt (see Fig.6). Such a lack of basal ductile layers is responsible of the development of a typical high-tapered foldbelt achieved by imbricate foreland-verging thrusts, in good agreement with analytic models of fold-and-thrust belts and accretionary wedges (Davis et al., 1983; Davis and Engelder, 1985). The individual thrusts ramp up through the entire Mesozoic sequence and do not employ subsidiary potential detachment levels provided by Callovian-Oxfordian and Berriasian marls.

The total amount of shortening documented in this section amounts to some 20 km.

Section 2: Southern Jura

This profile, which extends from the Savoy Molasse Basin to the autochthonous Cémieu High, crosses structural elements characterized by different transport directions; therefore, strictly speaking, it cannot be balanced.

The internal Jura is characterized by large ramp-anticlines involving the entire Jurassic sequence, such as the Gros Foug and Grand Colombier structures, which are detached from the autochthon at a Keuper salt level. Smaller folds and back-thrusts are attributed to the activation of secondary detachment horizons. Syn-tectonic Molasse series date the onset of folding as Burdigalian (Deville et al., 1994), in the eastern part of the section.

The external, thrust zone is separated from the internal zone by the broad Valromey syncline in which Neocomian strata are preserved. The change in structural style observed in the frontal imbricated zone is related to the pinch-out of Keuper salts against the Ile Crémieu High, to thinning of the Jurassic sequence due to Paleogene erosion and possibly to overprinting of extensional fault systems forming part of the Bresse Graben. In the more internal parts of this zone, upright detachment folds, evolving into pop-up structures, are cored by massif salt.

On the basis of serial cross-sections in the southern Jura (Philippe, 1995), the total amount of westwards displacement of the Jura-Molasse Basin boundary along this profile is of the order of 22 km

Section 3: ECORS profile

This cross-section is constrained by the Jura-Bresse ECORS deep reflection-seismic profile (Guellec et al., 1989, 1990a and 1990b; Damotte et al., 1990; Bergerat et al., 1990; Roure et al., 1989; Truffert et al., 1990). It crosses obliquely the sinistral Vuache-Les Bouchoux wrench zone (Blondel et al., 1988; Charollais et al., 1983; Wildi et al., 1991) which is characterized by significant Miocene offsets of about 6 km (higher estimated

value; Philippe, 1995); this impedes perfect balancing of this section.

The architecture of this sector of the Jura Mountains is characterized by a northwest verging external imbricated zone, which overrides extensional structures of the Bresse Graben, and an internal zone characterized by thrusts and back-thrusts. Folds play a very subordinate role. The internal zone of the Jura is clearly elevated with respect to its external zone and the Molasse Basin. This is quite probably the consequence of partial inversion of a Permo-Carboniferous trough during the late Jura deformation phases. The presence of such a trough is indicated by the ECORS profile and the results of the Charmont well, which bottomed in Permian red beds. As this partly inverted trough appears to be strike oblique the axes of the thin-skinned fold axes defined in the Mesozoic series, its deformation probably occurred after the main phase of the Jura deformation (Philippe, 1994, 1995).

Total shortening measured in the detached cover in this section amounts to about 32 km.

Section 4: Mont Tendre - Grozon High

This section is constrained by a number of deep wells and partly also by reflection-seismic data. It clearly illustrates the changes in structural style between the internal and external zone and the occurrence of intervening, little deformed plateaux.

There is no evidence in this section for inversion of a Permo-Carboniferous trough. The activation of Keuper evaporites as the major detachment horizon is indicated by wells Laveron-1 and Toillon-1 which penetrated more than 800 m thick salt. A second, important detachment level corresponds to Early Jurassic shales, as evident by the well Risoux-1 (see Fig. 7a). The bulk of shortening achieved in this section is accommodated by folding and major thrusting in the internal zone, characterized by the Mont Tendre and Risoux nappes, and by semi-rigid translation of the external zone which overrides the Bresse Graben margin by about 7 km near Lons-le-Saunier (Chauve et al., 1988). The allochthony of the Lons, Champagnole

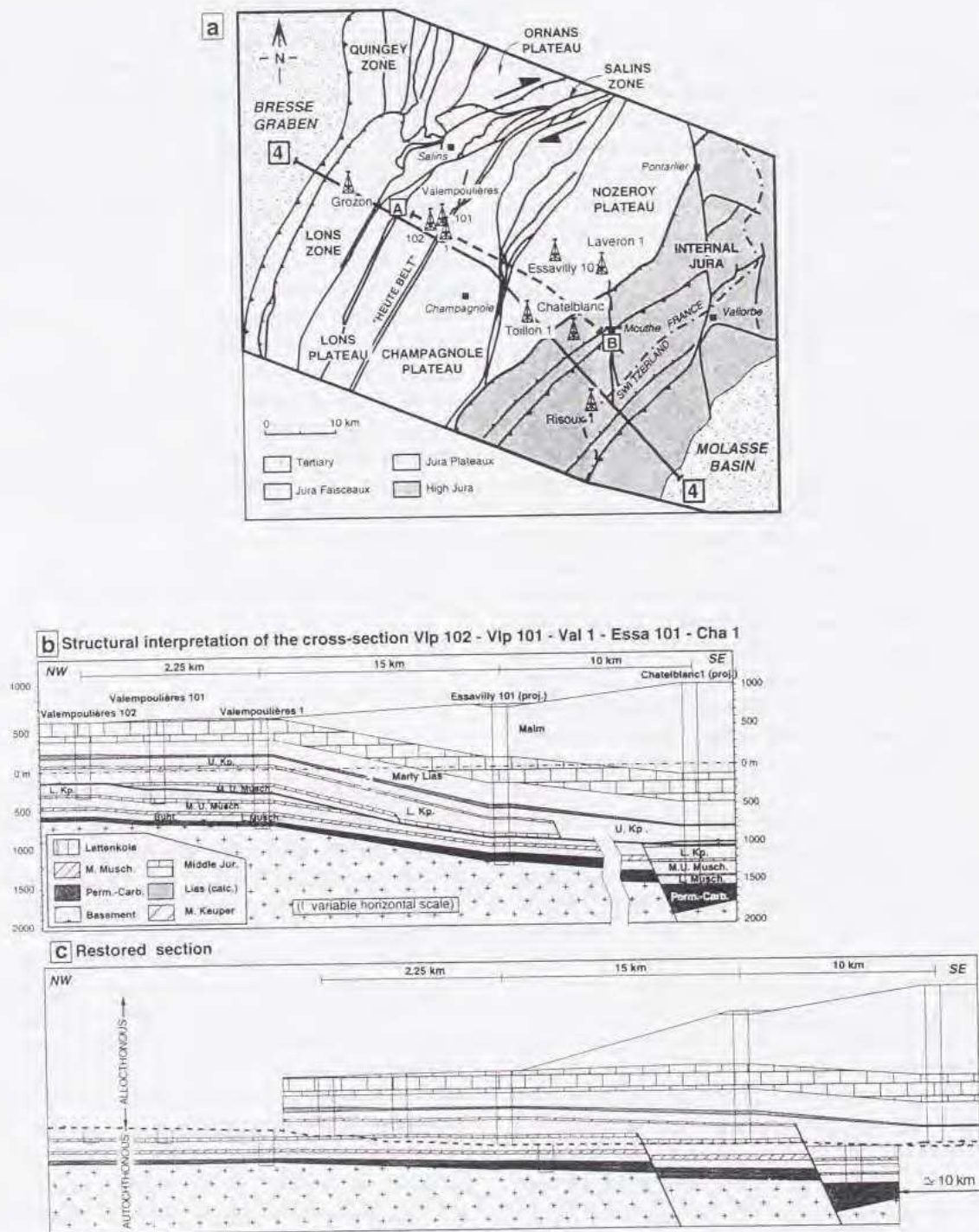


FIG. 7. **a)** Schematic structural map of the Valempoulières area.
b) Structural correlation between selected boreholes along a NW-SE transect.
c) Restoration of the previous section.

and Nozeroy plateaux, which were transported northwestwards by more than 10 km along an intra-Triassic sole thrust, without being substantially deformed, is indicated by wells drilled in the Valempoulières gas accumulation, which produce from Muschelkalk dolomites, and the wells Essavilly-101 and Chatelblanc-1 (Fig. 7b). As this flat laying thrust plane cuts along trend downwards from a middle Keuper level in the south into the Muschelkalk before rising back to a Keuper level to the north, it probably intersected a set of extensional faults which were active either during Late Triassic-Early Jurassic or possibly Eo-Oligocene times (Fig. 7c).

The total amount of shortening in this section is of the order of 32 km.

Section 5: Lake Neuchâtel - Ognon fault system

Sedimentary thicknesses and the basement gradient shown in this profile are constrained by the wells Orsans-1 and Buez-1 drilled in the external Jura and the well Treycovagnes-1 located in the Molasse Basin. There are no reflection-seismic data available for this transect.

The internal zone of the Jura is characterized by a succession of major north verging faulted folds and associated back-thrusts. These are assumed to be detached from the autochthon at the level of Middle Triassic Muschelkalk salts. The geometry of these folds suggests a first phase of asymmetric detachment folding involving salt flowage in their cores, followed by a phase of fault-propagation folding. There is no evidence for major thrust sheets as seen in section 4, suggesting along-strike northeastwards gradual disappearance of the Mont Tendre and Risoux nappes. The external Jura is characterized by a large number of NNE-SSW striking sinistral wrench faults (Fig. 2); most of these faults developed during the Eocene compressional event ("Pyrenean phase") and were reactivated as normal faults during the Oligocene extension. During the deformation of the Jura, many of them were transpressionally reactivated as sinistral strike-slip faults within the detached cover as it was displaced to the northwest (Tschanz, 1990; Philippe, 1995). The Jura deformation front

is marked by a set of small anticlines, striking parallel to the orocline, and a large number of NNE-SSW striking faults which form part of the Rhin-Saône transform zone. Basement faults delineating possible Permo-Carboniferous troughs, were apparently reactivated during Oligocene times and thus provided for discontinuities in the Triassic detachment levels. As such they guided the location of the frontal Besançon and Ognon zones.

Cumulative shortening in this cross-section is about 21 km.

Section 6: Grenchen Anticline - Rhine Graben

This section is essentially based on the one published by Buxtorf (1916) and an industry-type seismic profile running across the "Ferrette Jura" and the southern part of the Rhine Graben. Both Keuper and Muschelkalk are involved in the fold and thrust structures of the Jura up to its northern deformation front where Paleogene sediments of the Rhine Graben are affected by folding, as seen in the Ferrette anticline. Muschelkalk salts acted as the major decoupling horizon between the autochthonous substratum and the allochthonous Jura.

This transect is characterized by a succession of box-folds, resulting from a complex interaction of faulting and buckling induced by the presence of an efficient basal ductile layer, controlling the mechanical behaviour of the overlying brittle strata, which, in turn, are interrupted by secondary incompetent layers, such as the Oxfordian clays; locally these account for disharmonic folding. A clear distinction between an internal and an external zone is difficult. The broad Delémont syncline can be considered as an internal plateau.

The total amount of shortening in this section is of the order of 12 km.

Section 7: Aarau - Tabular Jura

This section extends from the Tabular Jura, which forms the sedimentary cover of the Black

Forest, across the narrow internal zone of the Jura which consists of two main thrust sheets; these have been pierced by a road tunnel. Reflection-seismic and well data indicate that the southern margin of the Jura Mountains closely coincides with the southern border fault of a major Permo-Carboniferous trough. Permo-Carboniferous faults were probably reactivated during the development of the Rhine Graben to the degree that they disrupted the Triassic detachment levels and thus nucleated north-verging thrusts during the Neogene deformation of the Jura (Laubscher, 1986). However, the offset on such faults was apparently insufficient to totally clamp down northwards propagation of the Jura deformation front. Northwards the basal sole thrust, which regionally is located within the Muschelkalk, rises into Keuper and Lower Dogger "opalinus-shales" (Bitterli, 1990; Jordan et al., 1990; Jordan and Noack, 1992).

The minimum estimated shortening in this section is about 6.5 km.

Section 8: Lägern anticline

The thrust Lägern anticline is the easternmost feature of the Jura orocline. Based on reflection-seismic data (Müller et al., 1984), it corresponds in this section to a typical detachment lift-off which is slightly overturned to the North (Mühlberg, 1894). A basal heterogeneity, offsetting the detachment level, is provided by a set of deep-seated normal faults located beneath the Lägern structure, coinciding to the southern border of a Permo-Carboniferous trough.

The Lägern anticline accounts for about 2 km of shortening; as it dies out to the east this value decreases to zero.

Based on the cross-sections discussed above, which are in part constrained by wells and seismic data, we fully adhere in principle to the thin-skinned distant push model proposed by Laubscher (1961, 1965) for the development of the Jura fold and thrust belt. In order to explain its position in the Alpine foreland, it is essential to analyze the areal distribution of Triassic salts which permitted detachment of the Mesozoic and younger strata

from their basement. Isopach maps of Middle Triassic Muschelkalk and the Late Triassic Keuper salts, constructed on the basis of well data, show a close coincidence with the geometry of the Jura orocline, especially in the south of the belt where the left-lateral transfer zone achieving the southern termination of the Jura thrust-belt is surimposed on the limit of Upper Triassic evaporites (Fig. 6). In the central and southwestern parts of the Jura, the main decoupling level is located at the base of the Keuper salts whereas in its northern and eastern parts middle Muschelkalk salts acts as the principal detachment horizon (Laubscher, 1961, 1986; Blondel et al., 1988; Guellec et al., 1990a and 1990b; Jordan, 1992; Philippe, 1994). Under the Molasse Basin, both salt layers decrease rapidly in thickness towards the south and disappear entirely near the Alpine deformation front.

The configuration of the external deformation front of the Jura fold- and thrust belt is highly variable. Whereas the margin of the Bresse graben is overthrust to various degrees, the external elements of the northern and northeastern parts of the Jura bump against the undeformed foreland, corresponding to the Tabular Jura (Fig. 2). The Ognon and Lomont fault zones appears to coincide with pre-existing normal fault systems which were partly inherited from Permo-Carboniferous times and were tensionally reactivated during the Paleogene subsidence of the Rhine-Bresse system of grabens. These fault systems played an important role in the nucleation of ramping-up thrusts. The southwestern swing-back and termination of the Jura fold-and-thrust belt was apparently preconditioned by the pinch-out of Keuper salts against the Ile Crémieu High. Similarly its northeastern termination is probably related to thinning of the Muschelkalk and Keuper evaporites below a critical thickness.

Theoretical and Analogue Model Considerations

Palinspastically restored cross-sections through the Jura fold-and-thrust belt and the Molasse Basin indicate that, prior to their deformation, they had the geometry of a northwestwards

tapering wedge which was underlain by a relatively smooth basement.

A possible explanation of both the interposition of the Molasse Basin between the Western Alps and the Jura foldbelt and contrasting structural styles of High Jura and Plateau zones can be provided by results of conventional models of accretionary wedges and fold-and-thrust belts.

Hubbert and Rubey (1959) showed that the maximum length of a rectangular body of rocks, undergoing rigid displacement on a horizontal plane, depends on the pore pressure at its base. From this follows that a thrust sheet, exceeding this critical length, will be internally strained according to its rheological properties. The critical taper model of Davies et al. (1983) stipulates that such internal deformation results in the development of an, in cross-section triangular, accretionary fold-and-thrust belt which continues to thicken until a critical taper is attained. Depending on the rheology and/or pore pressure at the base of the

undeformed foreland sedimentary wedge, the latter can be detached from the basement and slides forward together with the internally deformed foldbelt (Fig. 8). In such a model the internal Jura corresponds to an accretionary foldbelt while its external zone represents the internally little deformed foreland wedge, the length of which depends, according to Hubbert and Rubey (1959), on the rheology of the detachment level. As at depths greater than 2 km and under geothermal gradients of 20 to 30°C/km the shear strength of salt is smaller than 1 MPa (Carter and Hansen, 1983), it is plausible that bulk detachment of the external Jura occurred once the internal Jura fold-and-thrust belt had attained a critical taper (topographic relief). Yet, as the external Jura has undergone considerable internal deformation, concentrated on pre-existing discontinuities, it cannot be regarded as a completely homogeneous rigid body, as assumed in the model of Hubbert and Rubey (1959).

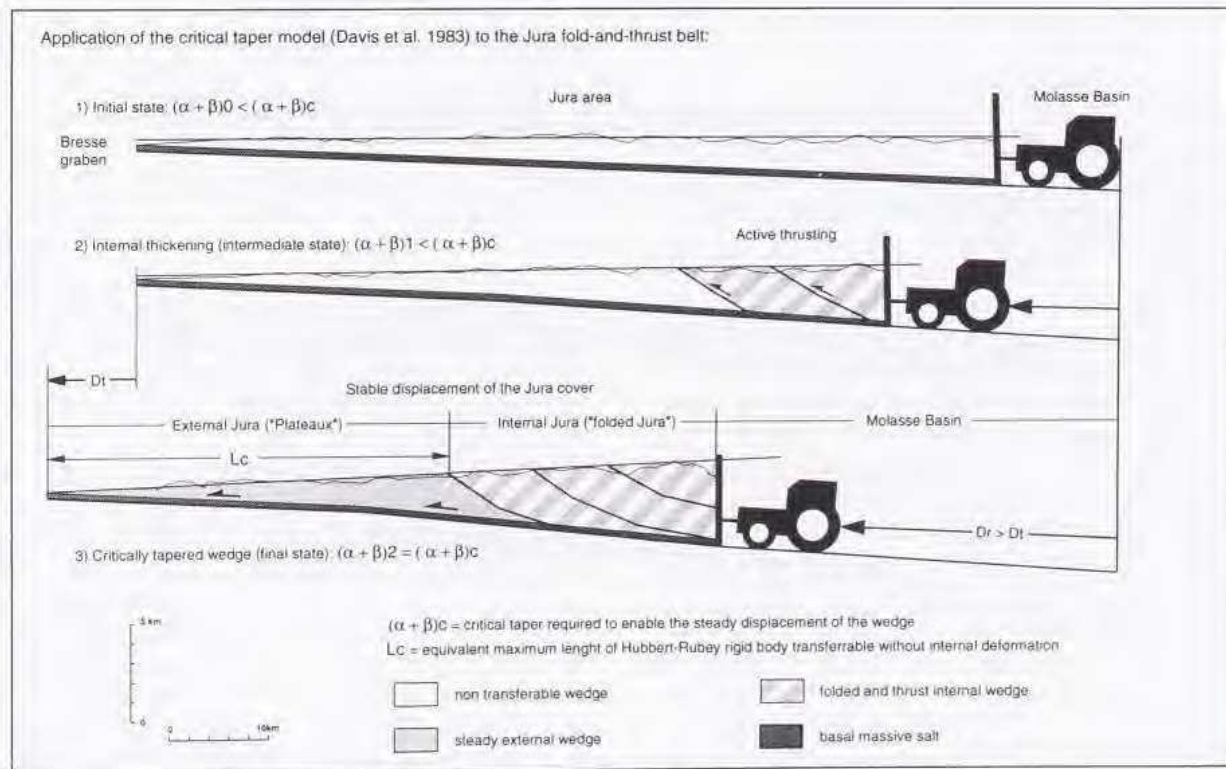


FIG. 8. Critical taper model of Davis et al. (1983) applied to the Jura fold-and-thrust belt.

However, as the Jura fold-and-thrust belt is separated from the Alps by the apparently little to undeformed Molasse Basin, the problem of stress transmission from the external Alpine massifs (Aar, Mont Blanc, Aiguilles-Rouges, Belledonne) to the Jura Mountains requires special attention (Laubscher, 1961, 1972; Mugnier, 1984; Mugnier and Vialon, 1986). To this end, a multi-layered analogue model was constructed in which limestones and sandstones are represented by sand and glass powder and rocksalt by silicon putty. The thickness of the basal silicon putty layer was varied according to the isopach of the Triassic salts. An essentially uniform thickness was assumed for the Mesozoic carbonates and shales. The Tertiary fill of the Molasse Basin was simulated by a left tapering wedge, pinching out near the middle of the model. The domain of the Jura Mtns. is represented by the left side of the model. This model was deformed at low strain rates (1-2 mm/h) by displacing a vertical back-stop from the right to the left, simulating the horizontal push of the external Alpine massifs. At several stages during the deformation of this model, transverse cross-sections were imaged by means of X-ray tomography (see Colletta et al., 1991).

Figure 9 shows the evolution in a vertical cross-section of this model and demonstrates that deformations are entirely concentrated on its left part, simulating the Jura thrust belt, whereas the right part, corresponding to the Molasse Basin, is moving to the left without undergoing internal deformation. It is also evident that deformations are initially concentrated near the thin end of the Molasse wedge but do not develop strictly in sequence. Unlike brittle models, which are characterized by in-sequence thrust propagation, models involving ductile detachment levels show a disorderly thrust sequence of thrust propagation and are characterized by the development of pop-up structures carried by fore- and back-thrusts (Ballard et al., 1987; Colletta et al., 1994). During the late stage of the model, deformation migrated towards its left boundary and stopped at the limit of the silicon layer representing Triassic salts; at the same time the more internal structures continued to grow. The final stage of the model bears considerable similarities with the structural style of the Central Jura.

From this analogue model we conclude that the combination of a tapering Molasse Basin wedge and the presence of a basal viscous layer is responsible for the stress transfer to the Jura Mountains. Whereas the initial taper of the undeformed Molasse wedge was equal to the critical taper, the initial taper of the internal parts of the Jura was below the critical taper. With progressive deformation of the internal Jura, the belt reached, in cross-section, a critically tapered prismatic shape and consequently its external parts (i.e. the so-called Plateaux) were detached from their substratum and transferred to the northwest over 10 km (see Encl. 1, section n°5).

3-Dimensional Palinspastic Restoration

3D restoration of oroclinal foldbelts has to contend with inherent space problems and requires detailed knowledge about the direction of mass transport in space and time.

Microtectonic analyses indicate a radially diverging mass transport (Fig. 10; Plessmann, 1972; Meier, 1984; Tschanz, 1990; Philippe, 1994, 1995) which is consistent with the trend of stress trajectories inferred from major fold axes (Laubscher, 1972). Palaeomagnetic data do not reveal noteworthy rotations (Johnson et al., 1984; Elderge et al., 1985; Gehring et al., 1991). Based on this, we conclude that the finite displacement map, derived from this data, reflects the centrifugal translatory motions of the different thrust elements making up the Jura fold-and-thrust belt, and that sinistral radial faults account for divergent compression in the external parts of this orocline. Lateral expulsion of Mesozoic series in the southern and northern Jura arc argues in favour of their decoupling from the autochthonous substratum. This is further supported by in situ stress measurements which demonstrate that the orientation of the principal horizontal compressional stress axes observed in the detached Mesozoic series differs from the one recorded on the underlying basement (Becker et al., 1987; Becker, 1989). Although the present stress field of Western Europe is dominated by NW directed trajectories of maximum horizontal compression (Müller et al., 1992; Rebai

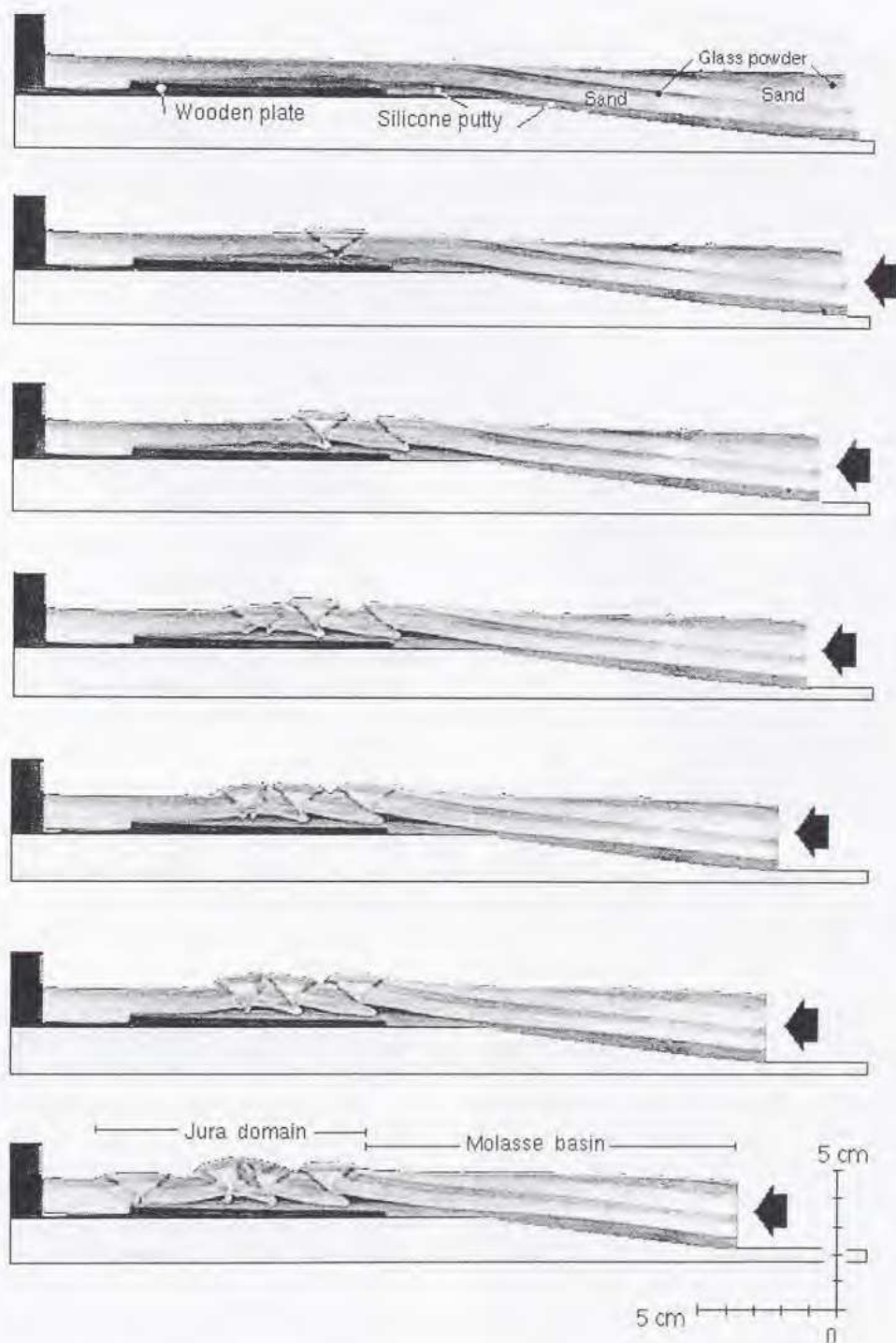


FIG. 9. Evolutionary cross-section of an analogue model simulating the horizontal push exerted by a backstop on the Alpine foreland (see text for explanation).

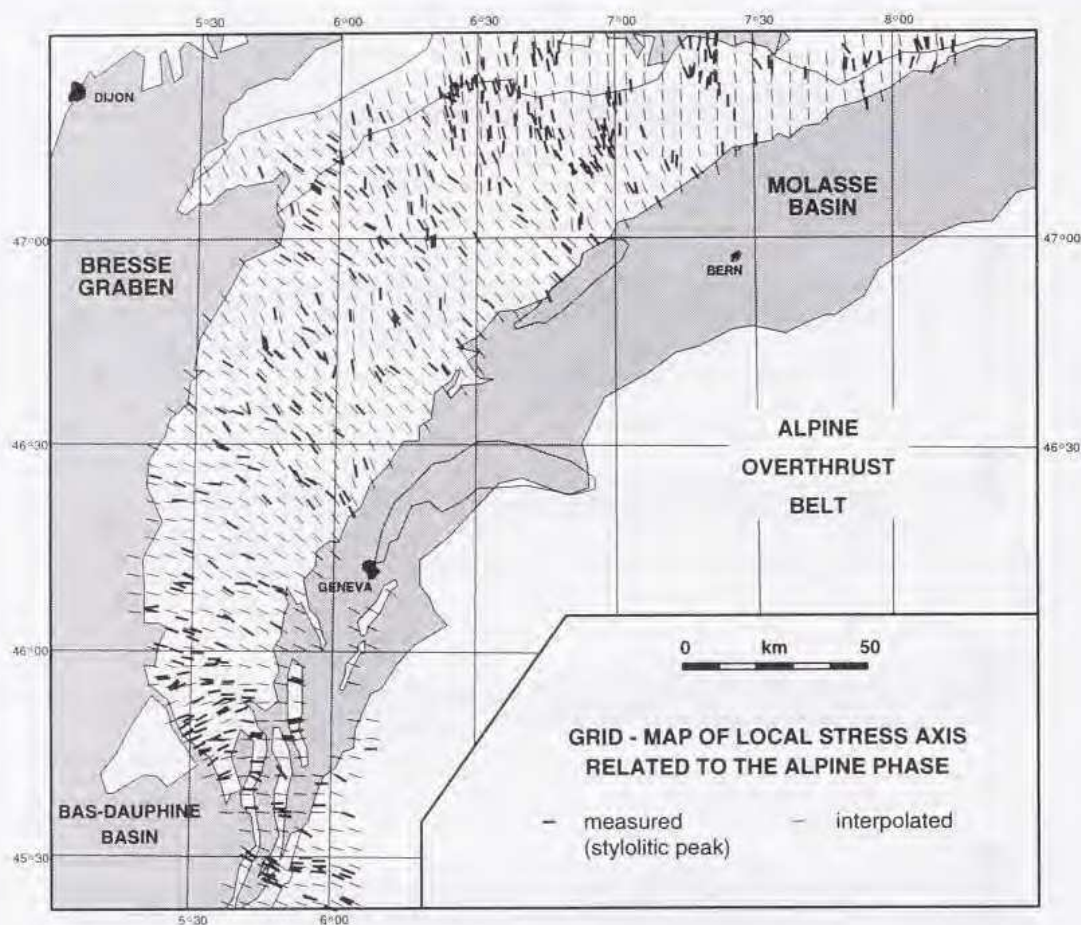


FIG. 10. Grid-map of the Mio-Piocene principal stress axes in the Jura fold-and-thrust belt based on stylolitics peaks (compiled after Plessman, 1972; Meier, 1984; Tschanz, 1990; Philippe, 1994; 1995).

et al., 1992), vertical strain-partitioning in the detached sediments of the northern Jura can deviate as much as 50° from this regional stress field.

We have applied the map balancing method developed by Laubscher (1965) and refined by Baby et al. (1993). In a first step the study area was subdivided into structural units delimited by frontal and rearward thrust faults and lateral strike slip faults (Fig. 11a). In a second step, the amount of shortening achieved within and between the different units (related to cumulative internal foldings and displacements along thrusts and back-thrusts) was derived from restored cross-sections (see Encls. 1 and 2); determined values may have an error margin of up to 25%, depending on the restoration method used. In the third step all units

were retrodeformed and moved back to their pre-deformation position along transport trajectories indicated by micro- and macrotectonics.

Iterative steps in retro-deformation of the Jura orocline show that, although radial forwards displacement of the different units played a dominant role, additional transpressional deformations along major wrench faults (from NW to SE: Caquerelle, Pontarlier-Valorbe, Vuache-Les Bouchoux and Culoz faults), resulting in small-scale rotations and/or shear deformation, must be invoked in order to explain the kinematic evolution of the arc. In view of the importance of these wrench faults, units bounded by them were linked into blocks as shown in Figure 11b. The transport trajectories implied by this final palinspastic model corre-

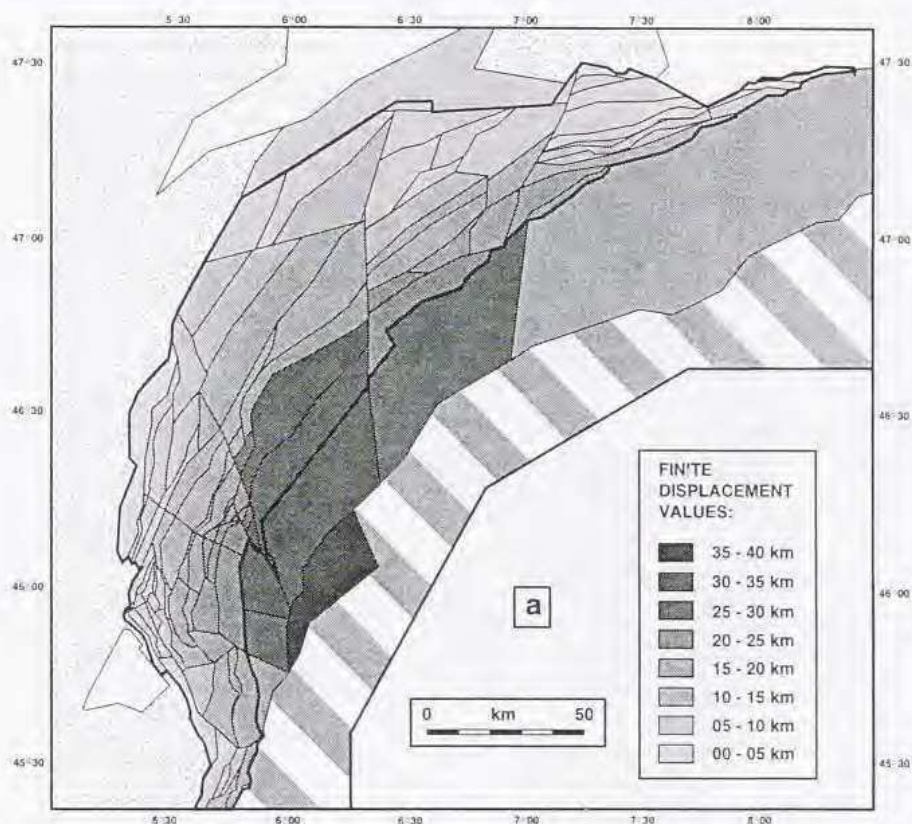


FIG. 11a. Structural map of the Jura fold-and-thrust belt divided in surface units. Finite displacement values are calculated from the Fig. 11b.

sponds closely with those derived from micro- and macrotectonic analyses (compare Fig. 11c and Fig. 12).

We conclude that radial, outwards diverging transport directions, facilitated by detachment of the Mesozoic and Cenozoic sediments from their basement and the early activation of a system of wrench faults facilitated the development of the Jura orocline. Some of these faults may correspond to pre-existing features (e.g. Vuache-Les Bouchoux fault; Charollais et al., 1983; Blondel et al., 1988; Rhine graben faults; Laubscher, 1981) whereas others (e.g. Pontarlier-Vallorbe fault; Laubscher, 1961) may have initiated during the early phases of the Jura deformation as their angular relationship to the strike of folds conforms closely to the Mohr requirement for lateral extension in a divergent system (Laubscher, 1972).

Our 3D palinspastic restoration of the Jura arc implies a 10° clockwise rotation of the Jura and

Molasse sedimentary prism around a pivot located near the eastern termination of the Lägern anticline (this was advocated already by Laubscher in 1965 who estimated the amount of rotation to about 7°). However, no longitudinal extension required south of this rotation axis is far from being demonstrated. Therefore, such a rigid clockwise rotation of the detached sediments of the Plateau Molasse is certainly in fact accommodated by significant wrench faulting and/or homogeneous dextral shearing deformation, as not illustrated by the proposed final palinspastic map (for further discussions, see Burkhard, 1990). A large number of (strike-slip?) faults seems to cross-cut the Molasse Basin, according to published tectonic maps (e.g. Matter et al., 1980; Jordan, 1992); Even so, their precise signification and implication in décollement tectonics of the Jura-Molasse nappe remains under considerations.

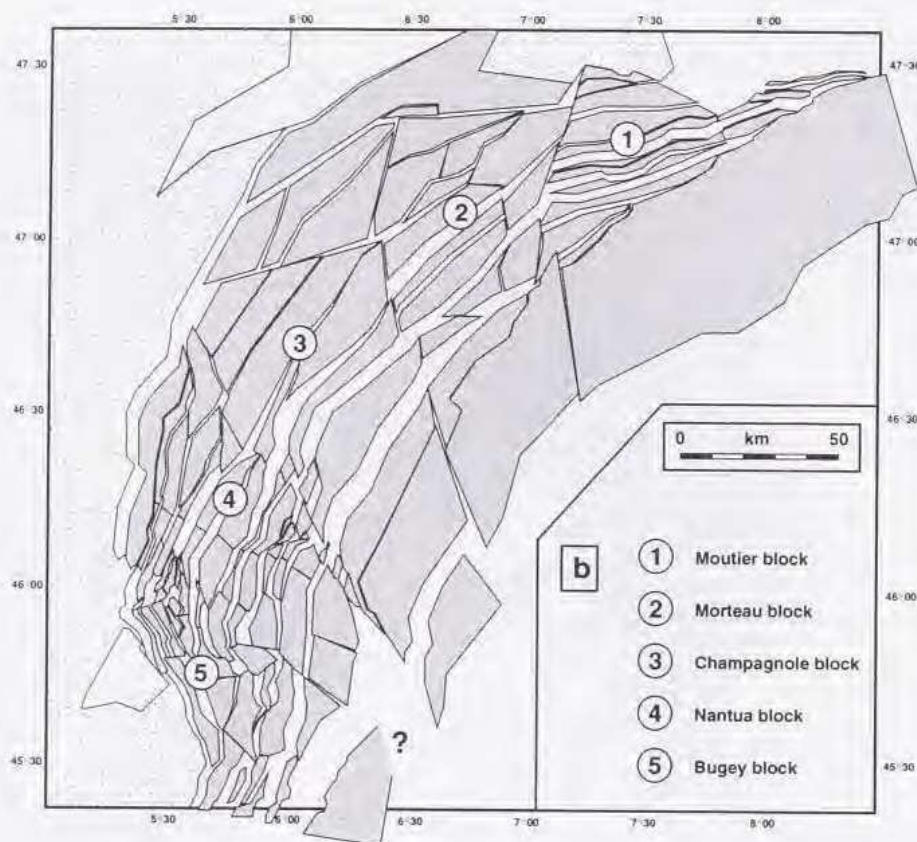


FIG. 11b. Final restored map.

Geodynamic Implications and Conclusions

Compressional stresses exerted on the Alpine foreland resulted in detachment of the Molasse Basin from its basement. Acting as a relatively rigid unit, its northwestwards displacement caused deformation of the sediments covering the Jura domain and uplift of the Molasse Basin (Laubscher, 1961; Müller and Briegel, 1980; Müller and Hsü, 1980; Trümpy, 1980). Lateral changes in bulk shortening achieved in the Jura orocline indicate a southwestwards increase in displacement of the Molasse Basin reaching a maximum of about 35 km south of Geneva where the Molasse Basin is internally deformed, as indicated by the Salève and Montagne d'Age ramp anticlines (Guellec et al., 1989, 1990a; Wildi and Huggenberger, 1993; Deville et al., 1994). In contrast, to the east of the Lägern, the structural style of the Molasse Basin is characterized by an orogen-ward dipping mono-

cline and a well developed thrust subalpine triangle zone (Bachmann et al., 1982; Burkhard, 1990; Stäubli and Pfiffner, 1991).

Large-scale clockwise rotational displacement of the Molasse Basin is assumed to be kinematically related to the coeval uplift of the basement-involving ramp anticlines forming the external Alpine Aar, Belledonne and Mont Blanc-Aiguilles Rouges massifs. These acted as crustal-scale mobile back-stops during the deformation of the Jura nappe (Ménard, 1977, 1988; Doudoux et al., 1982; Roure et al., 1989; Guellec et al., 1990a). Neogene differential westwards displacement of the Belledonne-Mont Blanc-Aiguilles Rouges block relative to the Aar Massif along the dextral Simplon-Rhône shear zone, located in front of the intra-Alpine Ivrea-Adriatic-Periadriatic lineament (Fig. 12), accounts for the observed strain increase in the central and southwestern parts of the Jura orocline. A schematic interpretative model about

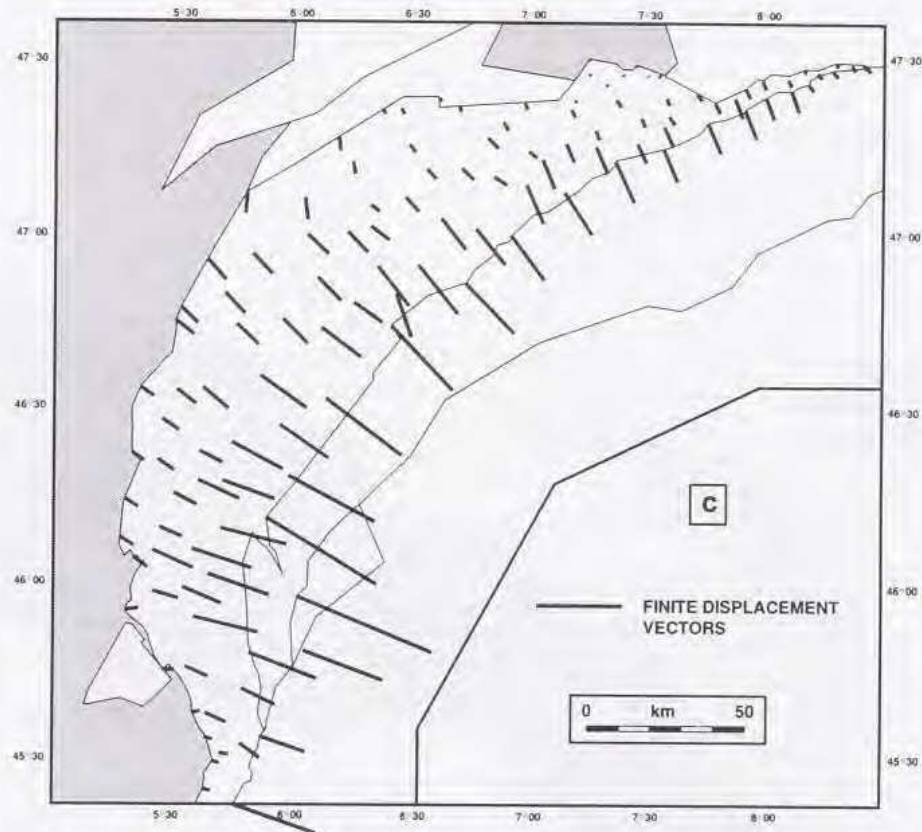


FIG. 11c. Finite displacement vectors derived from Figure 11b.

the geodynamic evolution of western Alps could be summarized as following:

- (1) northwards motion and counterclockwise rotation of about 34° of the Apulian promontory,
- (2) westwards thrusting and counterclockwise rotation of about 25° of the external Alpine massifs (lateral expulsion in front of the Apulian promontory),
- (3) right lateral movements along the Simplon-Rhône Line between Aar-Gothard and Mt. Blanc-Belledonne massifs. It immediately follows
 - a clockwise rotation of about 10° of the Plateau Molasse.
 - indentation, shortening and displacement of the thin Jura cover towards the north-west, and

• centrifugal thrusting in the external parts of the Jura thrust belt accommodated by the onset of radial left-lateral strike-slip faults (strain-partitioning).

The set of surface and subsurface data at our disposal upon which we based the interpretations lead to the following outcomes:

(1) The development Jura fold-and thrust belt is governed by the distribution of Triassic evaporites, particularly rocksalt; the major transfer zone accommodating the southern termination of the belt is superimposed on the southwestern limit of the Keuper evaporites. All direct observational data show that the oldest rocks exposed in the Jura and implied by folds and thrusts are Triassic evaporites. This is also supported by distinct geometric analysis of some folds for which the calculated depth of detachment is in any case closely connect-

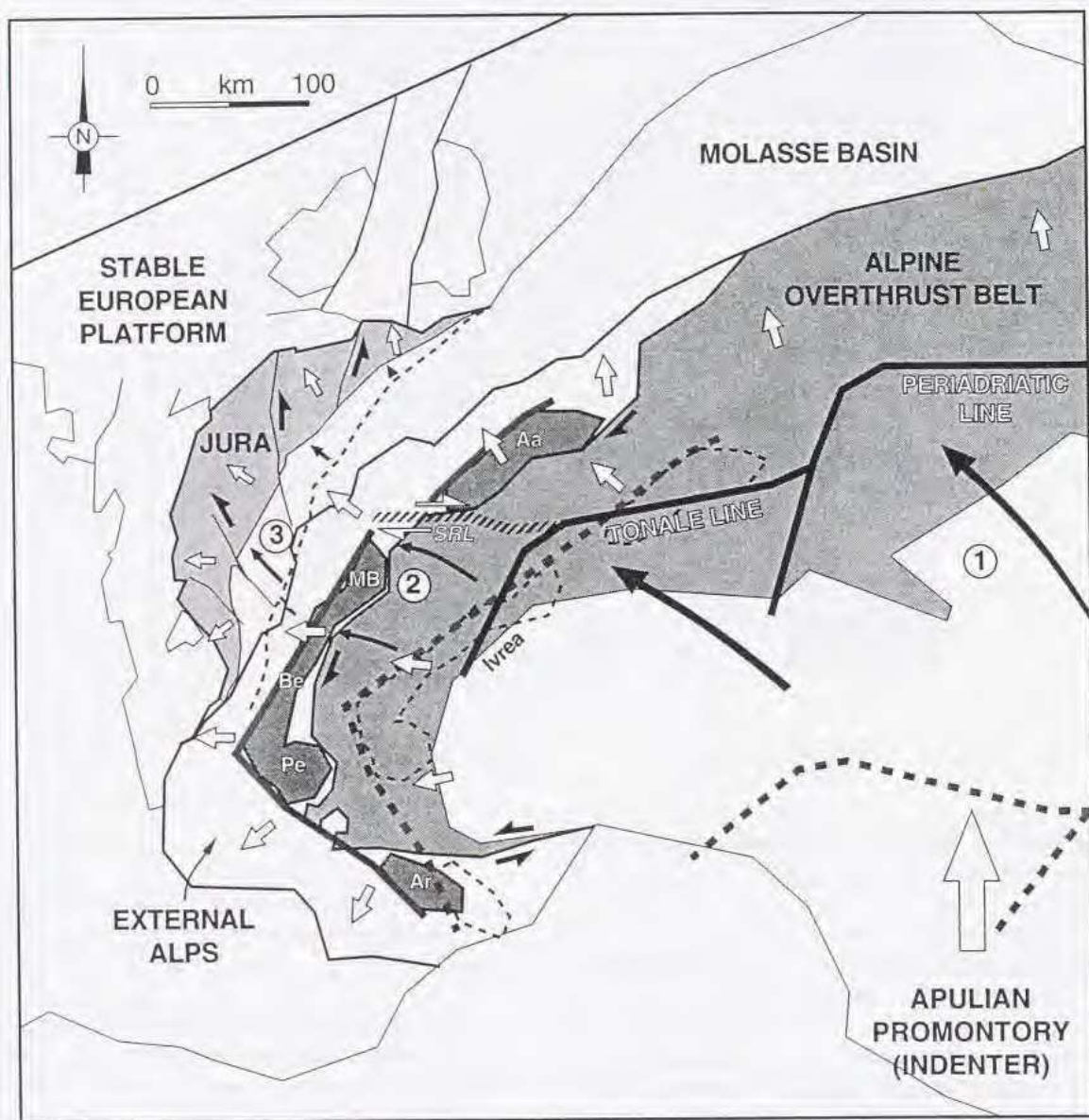


FIG. 12. Megatectonic map illustrating indenter effect of West Alpine arc and position of Jura fold-belt relative to the External crystalline massifs and Simplon-Rhône line (see text for explanation).

The palinspastic reconstitution of the Periadriatic line and External crystalline massifs is based on Vialon et al. (1989).

SRL: Simplon-Rhône Line.

External Crystalline massifs: AA: Aar-Gothard massif; BEL: Belledonne; MB: Mont Blanc - Aiguilles-Rouges massifs; Pe: Pelvoux massif.

ed to the location of Triassic evaporites (Laubscher, 1965, 1977; Mitra and Namson, 1989; Epard and Groshong, 1993). The Risoux 1 well, located on top of an abnormal structural high in the central Jura (see Encl. 1, section n°4), has revealed a duplication of the Mesozoic cover thanks to a major flat using Keuper salt and/or Early Jurassic shales. Moreover, a large number of drillholes have evidenced northwestwards displacement of about 10 km of the Mesozoic cover above a regional Triassic décollement level, both in the central Plateau zone (Fig. 7) and the western frontal part of the thrust belt (Michel et al., 1953; Chauvé et al., 1988, see Encl. 1, section n°4).

(2) The arcuate shape of the Jura thrust belt and the radially diverging mass transport of the Mesozoic cover is clearly indicated by microtectonic analysis (Fig. 10) and measurements of in situ rock stresses.

(3) The set of regional cross-sections presented in Enclosures 1 and 2 demonstrates significant lateral changes in the deformation style of the Jura fold-and-thrust belt. These are largely related to the nature of the detachment level, the amount of bulk shortening and the thickness and rheological composition of the deformed Mesozoic sequence, without taking into account a significant involvement of basement. Lateral changes in bulk shortening measured in the Jura cover is only made possible if the latter is completely decoupled from its basement.

(4) As evidenced by industry-type reflection-seismic lines and the ECORS Alp-2 profile (Guellec et al., 1990a and 1990b; Deville et al., 1994), the Salève and Montagne d'Age anticlines emerging through the Savoy Molasse Basin, correspond to typical fault-propagation folds related to a sole thrust hosted in Keuper beds, thus demonstrating detachment of the Mesozoic and Cenozoic strata from the basement at the level of Triassic evaporites beneath the Molasse Basin. In the same way, reflection-seismic data in the eastern Jura (Müller et al., 1984; Laubscher, 1986) have clearly imaged decoupling between the post-Triassic cover and its basement (see Encl. 1, sections n°7 and n°8). This is fully supported by microscopic analysis of important shear zones in the basal Triassic evaporites, encountered by boreholes in the Plateau Molasse south of the eastern Jura (Jordan, 1992).

(5) The critical taper of a thrust wedge is related to the basal shear strength and in the Jura it is so low as to almost disappear. The only rocks which can provide such a low shear strength are evaporites, especially salt. Where evaporites are lacking, as below the western Chartreuse massif, where décollement follows Triassic or Liassic shales, the critical taper increases dramatically and thrust sheets are piled up on each other. As evaporites underlie Molasse Basin, they provide detachment of the latter rather than a highly tapered pile of thrust sheets at its southern margin.

(6) Simple viscous-brittle analogue models validate the dynamic arguments based on observed critical taper and are able to simulate deformation of the Jura nappe system, of which the Molasse Basin apparently forms an integral part. Moreover, they demonstrate the role of obstacles in the décollement layer for nucleation of thrusts. Such obstacles have been found to consist of faults and flexures of the Rhin-Saône transform zone (Laubscher, 1986; Noack, 1989; see Encls. 1 and 2, sections n°5, n°7 and n°8). Intrabasement thrusting would not be affected in this way, as no weak layer parallel to the top basement can reasonably be expected to have been present and displaced in a way analogous to the Triassic evaporites. To a certain extent, Late Paleozoic coalbeds could provide décollement of the Molasse Basin but such rocks are far from being uniformly distributed over the whole area; therefore they cannot be assumed to play a role comparable to that of Triassic evaporites.

On the basis of reflection-seismic data from the Molasse Basin, an alternate model is advanced by some of our Swiss colleagues: they propose an intra-crustal sole thrust, rooted along the northern margin of the Aar Massif, which extends through the Molasse Basin (Ziegler, 1982, 1990; Gorin et al., 1993; Ziegler et al., this volume) and Jura thrust belt (Pfiffner and Erard, 1995). This is resolutely opposed to our postulates developed above regarding a theory on Jura development. Although we advocate a late basement involvement in Jura deformation, there is no comparison between the amounts of horizontal shortening measured in folded and thrust sediments and in the pre-Triassic substratum where it is closed to zero. After having considered all possible angles and, keeping in mind, that all our interpretations hardly depend on

data available from the Molasse Basin, we therefore see no other viable model except that of thin-skinned décollement on Triassic evaporites, i.e. the distant push model initially proposed by Laubscher (1961) for the Jura-Molasse nappe.

Acknowledgements- This work forms part of a thesis granted by and carried out in the *Department of Geology and Geochemistry of the Institut Français du Pétrole*. P.A. Ziegler is gratefully acknowledged for his generous involvement in considerable improvements of the initial manuscript. We are indebted to H.P. Laubscher and P. Jordan who provided helpful comments and suggestions.

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Enclosures

Enclosure 1 Regional balanced cross-sections through the Western Jura and western Chartreuse subalpine chain (location on Fig. 2).

- n° 1: Eastern Chartreuse massif - Bas-Dauphiné basin
- n° 2: Savoy Molasse basin - Ile Crémieu High
- n° 3: ECORS profile (Guellec et al., 1990a and 1990b; modified)
- n° 4: Mont Tendre - Grozon high (Winnock, 1961; Laubscher, 1965; Bitterli, 1972; Martin, 1987; Guellec et al., 1990b; modified)

Enclosure 2 Regional balanced cross-sections through the Central and Eastern Jura (location on Fig. 2)

- n° 5: Neuchâtel lake - Ognon fault system
- n° 6: Grenchen anticline - Rhine Graben (Buxtorf, 1916; modified)
- n° 7: Aarau- Tafel Jura (Mühlberg, 1894; Buxtorf, 1916; modified)
- n° 8: Lagern anticline (Mühlberg, 1894; Müller et al., 1984; modified)